pumped by the 9P36 line as measured with our system. The pressures were measured with a thermocouple gauge. For comparison, maximum output power for the 118.8 μ line was obtained at a pressure of 260 mtorr.

The dominant output power for this cavity is in a linearly polarized EH_{11} hybrid mode [6]. The polarization of this mode was determined in several cases using a piece of black polyethylene which was found to have polarizing properties from reported data on other known output wavelengths.

Finally, we wish to point out that the 46.7 μ line obtained by pumping CH_3OD with the 9R8 line has an output power comparable to the 118.8 μ line from CH_3OH. Crude estimates of output powers for both laser lines are in the 30 mW range for pump powers of about 10 W. While the conversion efficiency is lower for the shorter wavelength, the magnitude of the output power is substantial.

REFERENCES

[1] M. Rosenbluh, R. H. Temkin, and K. J. Button, "Submillimeter laser wavelength tables," *Appl. Opt.*, vol. 15, pp. 2635-2644, 1976.

[2] B. L. Bean and S. Perkowitz, "Complete frequency coverage for submillimeter spectroscopy with optically pumped CH_3OH, CH_3OD, CD_3OD, and CH_2CF_2," *Opt. Lett.*, vol. 1, pp. 202-204, 1977.

[3] S. F. Dyubko, V. A. Svich, and L. D. Fesenko, "Submillimeter CH_3OH and CH_3OD lasers with optical pumping," *Sov Phys. Tech. Phys.*, vol. 18, p. 1121, Feb. 1974.

[4] S. Kon, T. Yano, E. Hagiwara, and H. Hirose, "Far-infrared laser action in optically pumped CH_3OD," *Japan. J. Appl. Phys.*, vol. 14, pp. 1861-1862, Nov. 1975.

[5] D. T. Hodges, F. B. Foote, and R. D. Reel, "Efficient high power operation of CW far-infrared waveguide laser," *Appl. Phys. Lett.*, vol. 29, pp. 662-664, 1976.

[6] —, "High-power operation and scaling behavior of CW optically-pumped FIR waveguide lasers," *IEEE J. Quantum Electron.*, vol. QE-13, pp. 491-494, June 1977.

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(6) A Double-Ended, Unstable Resonator Submillimeter Laser,

T. F. EWANIZKY, W. T. BAYHA AND R. S. ROHDE

(12) 3

Abstract—**The characteristics of a pulsed, methyl fluoride laser utilizing a novel, double-ended unstable resonator are described. The design incorporates an intracavity, double-faced scraper mirror to produce separate input/output ports for CO_2 pump laser excitation and submillimeter laser output. Experimental results show that this configuration achieves state-of-the-art conversion efficiency and diffraction-limited beam quality.**

I. INTRODUCTION

An unstable resonator, methyl fluoride laser pumped by a multimode CO_2 TEA laser is described. This design for a submillimeter (SMM) laser features an intracavity, double-faced scraper mirror, which produces a double-ended optical configuration. Fig. 1 depicts the arrangement of the optical components and illustrates the design parameters. The system essentially forms a positive-branch, confocal, unstable resonator. If the scraper mirror were placed at the convex mirror position, at $\alpha = 1$, only single-ended, collimated-wave output would result as in a conventional system. Conversely, if $\alpha = 0$, only spherical-wave output would be emitted. Intermediate placement of the scraper mirror produces varying amounts of both collimated and spherical-wave output, depending on the value of α. Chodzko *et al.* [1] utilized this feature for coupling an unstable resonator to an external, annular gain medium.

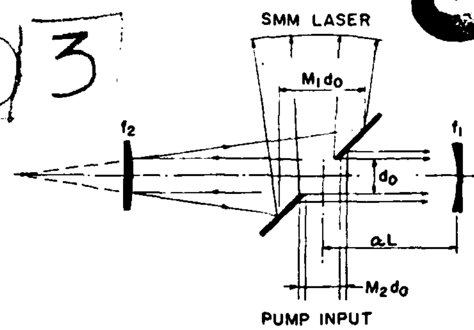

Fig. 1. Schematic diagram of the double-ended unstable resonator, illustrating the spherical and collimated-wave mode dimensions and defining the design parameters. The center of curvature for the spherical-wave output mode is coincident with the focal point of the convex mirror f_2.

For our application, the collimated-wave mode is used instead as a separate input port for an annular CO_2 laser pump beam, and the spherical-wave mode is used to derive separate SMM output from the internal molecular laser medium. The CO_2 pump beam enters the resonator as a collimated-wave, but propagating in the "backward" direction. It is demagnified in transverse dimension with each resonator round trip,

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thus producing radially symmetric excitation of the internal volume.

II. Resonator Description

There are a number of practical advantages to this concept. Separate input and output ports for the CO_2 pump beam and the SMM radiation allow the use of easily obtainable window materials which need only be transmissive at the separate wavelengths. Resonator mirrors are totally reflecting and thus can be of simple metal construction. Most importantly, since both the collimated and spherical-wave modes share a common internal volume, the resonator simultaneously presents an efficient cavity system for both excitation and SMM oscillation. Because of the radially expanding nature of unstable resonator modes, this advantage is maintained for arbitrary transverse dimension, making the system easily volume scalable.

Useful SMM radiation is derived from the spherical-wave output, while collimated SMM output is typically lost through absorption in the input window material. Fortunately, this loss can easily be minimized to an acceptable level by prudent choice of the design parameters. Because of the internal scraper mirror position governed by the parameter α, the double-ended unstable resonator is characterized not only by the optical magnification M, but also by the spherical and collimated-wave magnification factors, M_1 and M_2, respectively. Their relationship can be derived through purely geometric considerations:

$$M = |f_1/f_2| \tag{1}$$

$$M_1 = M - \alpha(M - 1) \tag{2}$$

$$M = M_1 M_2 \tag{3}$$

where f_1 and f_2 are the focal lengths of the concave and convex mirrors, respectively. The resonator length is given by the confocal condition $L = f_1 + f_2$.

The geometric output coupling fraction for the spherical wave is

$$\gamma_s = (1 - 1/M_1^2) \tag{4}$$

and for the collimated wave

$$\gamma_c = (1 - \gamma_s)(1 - 1/M_2^2). \tag{5}$$

Note that $\gamma_s + \gamma_c = (1 - 1/M^2)$, which is the geometric output coupling fraction for any confocal unstable resonator of magnification M. That is, the total geometric output coupling is only a function of the factor M. Fig. 2 shows γ_s and γ_c versus M_1, for various values of M. Note that by choosing a relatively large value of spherical-wave magnification M_1, the collimated SMM output loss can be reduced to tolerably small values.

Using available optics, our resonator was constructed from 50 mm diameter gold-coated metal mirrors, with $f_1 = 53$ cm and $f_2 = -14$ cm, giving $M = 3.79$ and a cavity length of $L = 39$ cm. The scraper mirror had an aperture diameter $d_0 = 1.91$ cm and was positioned to give $\alpha = 0.397$. These component dimensions fixed the resonator parameter values as $M_1 = 2.68$, $M_2 = 1.41$, and the output coupling fractions $\gamma_s = 0.86$ and $\gamma_c = 0.069$. An NaCl window was used for the CO_2 laser input port, and 2 mm thick polyethylene was used for the SMM output port window.

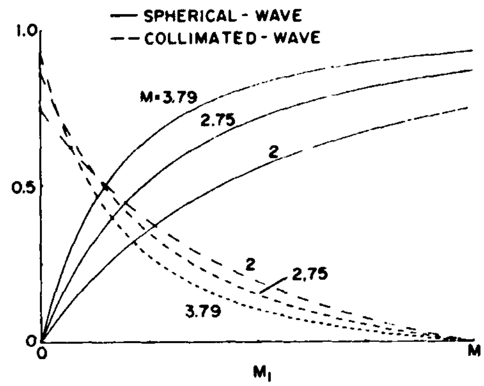

Fig. 2. Spherical and collimated-wave geometric output coupling γ_s and γ_c as a function of M_1, for various values of M.

III. Experimental Procedure

Lineup was accomplished with an unexpanded He-Ne laser beam reflected into the resonator, toward the concave mirror, from the edge of the scraper mirror aperture. With proper end mirror orientation, the reflected beam is walked into the resonator axis and emerges as a close analog to the laser mode. The mirrors are adjusted until the He-Ne radiation is emitted in a uniformly illuminated annulus from both the spherical and collimated-wave output ports.

An aluminum coated collection mirror was used to focus the spherical-wave lineup beam radiation to an image plane that was found to correspond to the image distance for a point source object located at the virtual center of the spherical wave, i.e., at the focal point of the convex mirror. The annular beam from a Lumonics Model 103-2 unstable resonator CO_2 TEA laser was made colinear with the He-Ne lineup beam, so as to correspond to the collimated-wave mode.

The CO_2 laser was tuned to the (9)P20 line, and pump energy entering the resonator in the collimated-wave mode was measured to be 1.14 J. A pyroelectric detector, with protective quartz filter, was located at the collecting mirror image plane to measure SMM radiation. A maximum value of 288 μJ was measured for an optimum gas pressure of 7-8 torr. This value is substantially higher than the 1-2 torr optimum pressures that have been reported for other methyl fluoride lasers [2], [3]. Fig. 3 illustrates the variation of SMM laser output versus methyl fluoride gas pressure. Apparently, because of the comparatively small excited volume within our system, net gain was maximized for an increased molecular density despite the attendant increase of rotational-level relaxation losses [3]. Although no spectral measurements were made, it is presumed that the SMM radiation consisted solely of the 0.496 mm transition at operating pressures greater than 5 torr [4].

Fig. 4 is an oscillogram of the SMM output pulse, made with a pyroelectric detector and oscilloscope of 10 ns combined risetime. The actual pulse is therefore somewhat shorter than the 35 ns FWHM duration measured, corresponding to a peak power greater than 8.2 kW. It is interesting to note that the SMM pulse shape is approximately Gaussian and smooth, with

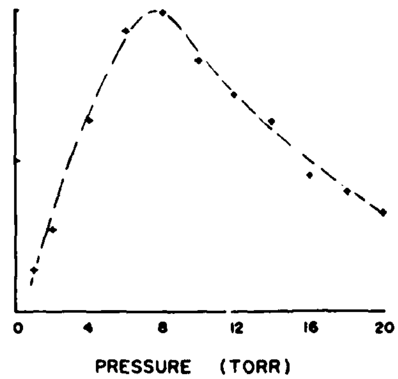

Fig. 3. Relative SMM laser output versus methyl fluoride gas pressure.

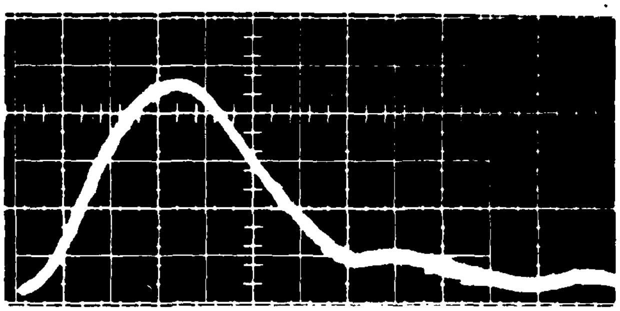

Fig. 4. Oscillogram of the SMM laser pulse, time scale of 10 ns/div.

no apparent spiking due to relaxation oscillation or mode beating. The slow modulation of the low amplitude tail is believed to be due to electrical noise. The SMM output pulse was found to coincide with the main 50 ns FWHM pulse of the CO_2 pump laser. It is estimated that this main pulse, alone responsible for effective SMM laser excitation, contains roughly 20 percent of the total measured pump energy. Using these figures, the calculated energy conversion efficiency is 0.13 percent, approximately within an order of magnitude of the Manley-Rowe limit.

Because the annular, spherical-wave laser beam has a phase-front curvature predominantly determined by geometric optics, direct analysis of its beam quality cannot be easily accomplished from measurement of the spot-size produced at the focal plane of a lens or mirror. If the virtual center of the spherical wave acts as a point source object, its diffraction-limited image should appear at an image plane determined by the mirror formula. Using a collecting mirror of 46 cm focal length, it was found that the SMM radiation indeed focused at an image distance of 67.5 cm, corresponding to the object distance of approximately 144 cm measured from the experimental arrangement. In fact, it focused at the same point in the image plane that was previously defined by the spherical-wave mode of the He-Ne lineup radiation, confirming the close analogy between the lineup and laser modes. Various diameter apertures were centered at this point and the transmitted energy measured for each case. 86 percent of the emitted energy was captured within an aperture of approximately 3 mm radius. This measurement can be readily compared with the theoretical performance of a Gaussian beam of equal initial dimension and phase-front curvature, focused by the collecting mirror [5]. This comparison shows that the SMM spot size was three times larger than that calculated for the corresponding Gaussian.

Consequently, we deduce that the annular SMM spherical-wave output could, in principle, be collimated to within three times the far-field divergence angle of a corresponding Gaussian beam. Based on this comparison, we further estimate that the SMM laser beam quality was diffraction limited, to at least within the limits of accuracy of our measurements, since this factor closely corresponds to the diffraction-limited divergence of an equally proportioned, plane-wave illuminated annulus [6].

IV. Discussion and Conclusions

We have described the design and operational characteristics of an unstable resonator SMM laser configuration whose conversion efficiency equals state-of-the-art SMM oscillators and emits radiation in a spherical-wave with diffraction-limited beam quality. It has the desirable properties of separate input and output ports, relatively compact configuration, and the requirement of only relatively simple optical components for its construction.

Limited by materials on hand, our resonator had a relatively high value $M = 3.79$. Together with the scraper mirror, whose aperture reasonably matched the pump beam annular dimensions, the resulting excited molecular volume was estimated to be less than 50 cm^3. From the standpoint of both increasing pumped volume and decreasing diffraction losses of the laser mode, a more optimum configuration would have greater transverse dimension and smaller M.

The SMM laser beam can be easily collimated, or focused, since it appears to have a simple spherical phase front, with virtual center at the focal point of the convex resonator mirror. Calculations made with a modified form of the Gaussian beam, ray-transfer matrix analysis technique [7], showed that the double-ended resonator had the same properties of spatial discrimination and length error tolerance as conventional positive-branch confocal systems.

Acknowledgment

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References

[1] R. A. Chodzko, S. B. Mason, and E. F. Cross, "Annular converging wave cavity," *Appl. Opt.*, vol. 15, pp. 2137-2144, Sept. 1976.

[2] T. K. Plant and T. A. DeTemple, "Configurations for high-power pulsed CH_3F 496-μm lasers," *J. Appl. Phys.*, vol. 47, pp. 3042-3044, July 1976.

[3] D. R. Cohn, T. Fuse, K. J. Button, B. Lax, and Z. Drozdowicz, "Development of an efficient 9-kw 496-μm CH_3F laser oscillator," *Appl. Phys. Lett.*, vol. 27, pp. 280-282, Sept. 1, 1975.

[4] D. E. Evans and L. E. Sharp, "Far-infrared superradiant laser action in methyl fluoride," *Appl. Phys. Lett.*, vol. 26, pp. 630-632, June 1, 1975.

[5] H. Kogelnik and T. Li, "Laser beams and resonators," *Appl. Opt.*, vol. 5, pp. 1550-1567, Oct. 1966.

[6] M. Borne and E. Wolf, *Principles of Optics*. London: Pergamon, 1970, pp. 416-417.

[7] T. F. Ewanizky, "Ray-transfer-matrix approach to unstable resonator analysis," *Appl. Opt.*, vol. 18, pp. 724-727, Mar. 1, 1979.